1. Radiative natural SUSY and
2. Post LHC8 SUSY benchmark points for ILC physics

1. HB, Barger, Huang, Mickelson, Mustafayev, Tata

2. Howie Baer (Oklahoma) & Jenny List (DESY)

Goals

1. provide assessment of post-LHC8 SUSY
2. is there still a role for ILC to play?

YES! precision measurements to be sure,

but also likely as a DISCOVERY MACHINE!

What are main SUSY lessons from LHC8?

1. discovery of SM-like Higgs scalar at m(h)~125 GeV confirms fundamental prediction of post LEP2 MSSM: m(h)~114-135 GeV

2. No sign of SUSY so far: e.g. in mSUGRA/CMSSM

$$m_{\tilde g} > 1\ TeV \ \ for\ m_{\tilde q} \gg m_{\tilde g}$$
$$m_{\tilde g} > 1.4\ TeV \ \ for\ m_{\tilde q} \simeq m_{\tilde g}$$

3. Seemingly violates predictions from many theorists: story of SUSY naturalness: sparticles ought to be below ~TeV

Little hierarchy problem: how can it be that m(Z)=91.2 GeV while sparticles > TeV?

New measure of naturalness:

how can m(Z)=91.2 GeV when sparticles >> TeV?

$$\frac{m_Z^2}{2} = \frac{(m_{H_d}^2 + \Sigma_d^d) - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2 \quad \simeq -(m_{H_u}^2 + \Sigma_u^u) - \mu^2$$

Each contribution to m(Z) relation ought be of order m(Z)!
i.e. no large cancellations amongst independent contributions to m(Z)

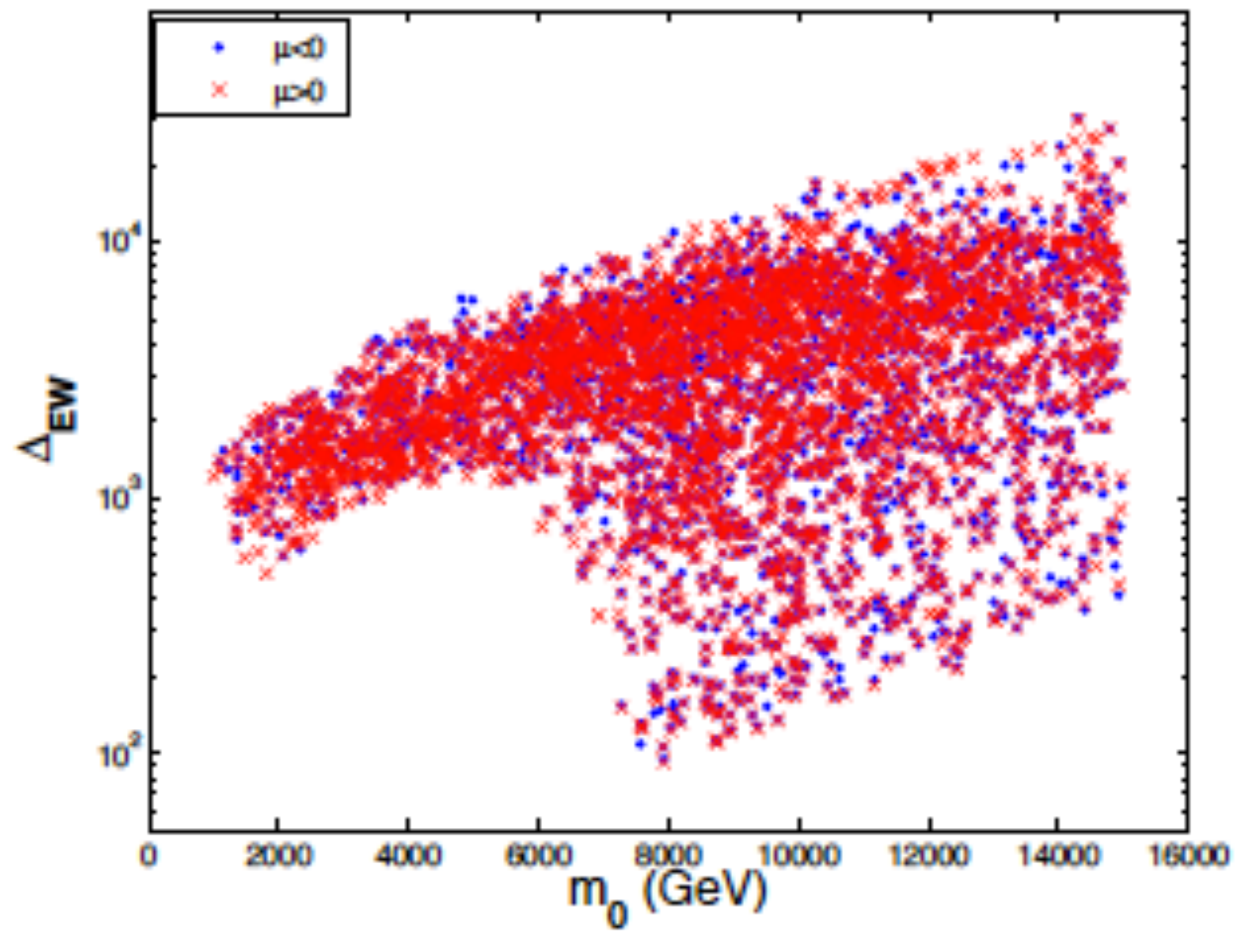
$$\Delta_{\rm EW} \equiv max(C_i)/(M_Z^2/2)$$

- Model independent (impose at weak scale!)
- Conservative (necessary but perhaps not sufficient)
- measureable (reconstruct from weak scale Lagrangian)
- unambiguous (depends on spectra not parameters)
- predictive [m(higgsino)~m(higgs)]
- falsifiable (no light higgsinos at ILC then SUSY EW naturalness dead)
- simple to compute (Isajet 7.83)

Requiring low Δ_{EW} rules out some old favorites

scan over mSUGRA

- mSUGRA
- mGMSB
- mAMSB



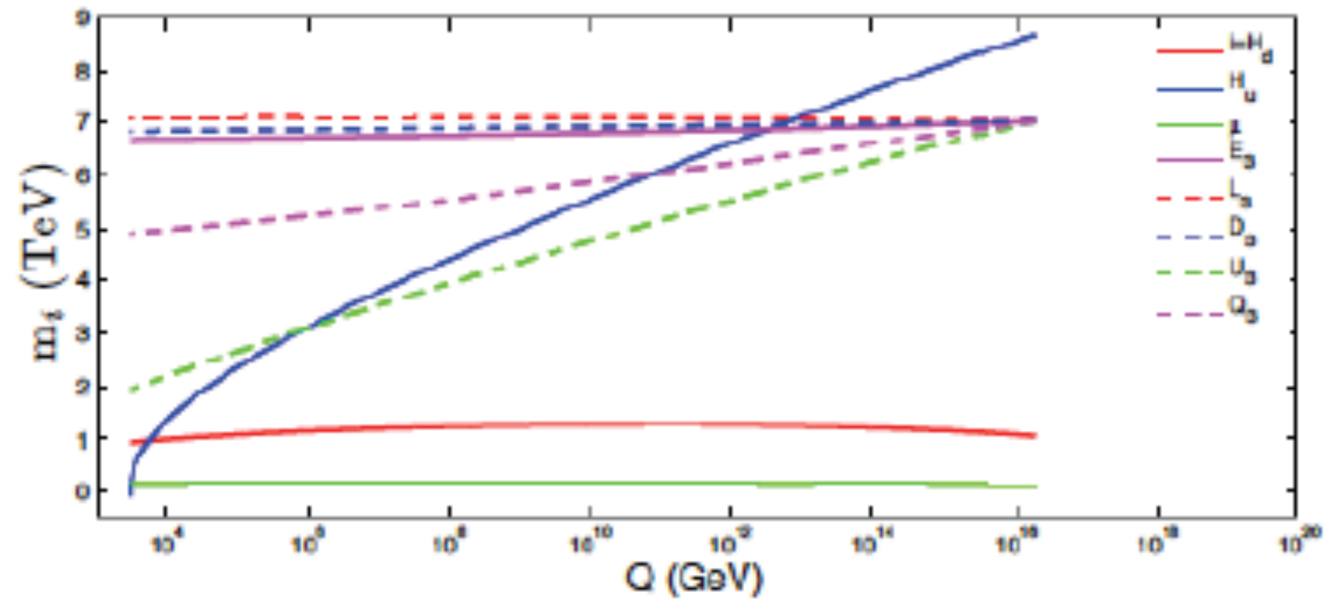
HB,Barger, Huang, Mickelson,Mustafayev, Tata, arXiv:1210.3019

LHC limits & m(h)=125 GeV => $\Delta_{EW} > 100 \; or \;\; < 1\% \; EWFT$

(All spectra from Isajet 7.83, Paige, Protopopescu, HB, Tata, hep-ph/0312045)

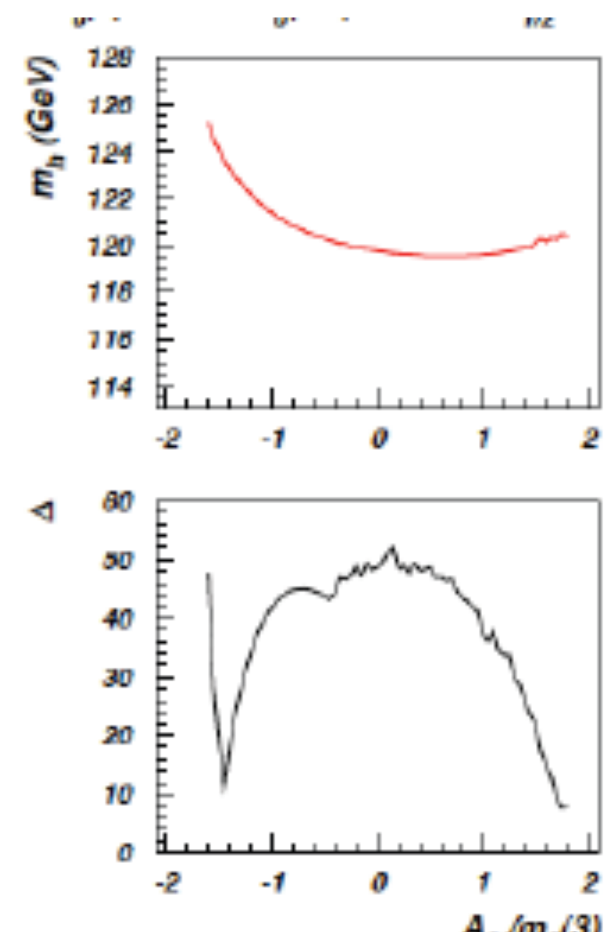
Radiative natural SUSY (from NUHM2)

- $\mu^2 \sim (m_Z^2/2)$
- $m_{H_u}^2 > m_0^2$
- $\Sigma_u^u(\tilde{t}_{1,2})\ small$



$$\Sigma_u^u(\tilde{t}_{1,2}) = \frac{3}{16\pi^2} F(m_{\tilde{t}_{1,2}}^2) \times \left[f_t^2 - g_Z^2 \mp \frac{f_t^2 A_t^2 - 8 g_Z^2 (\frac{1}{4} - \frac{2}{3} x_W) \Delta_t}{m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2} \right]$$

$$F(m^2) = m^2 \left(\log(m^2/Q^2) - 1 \right), \text{ with } Q^2 = m_{\tilde{t}_1} m_{\tilde{t}_2}$$



large stop mixing softens both t1 and t2 radiative corrections while increasing m(h) up to 125 GeV!

HB, Barger, Huang, Mickelson,Mustafayev, Tata
PRL109(2012)161802 and arXiv:1212.2655

Compare RNS to mSUGRA for similar parameters

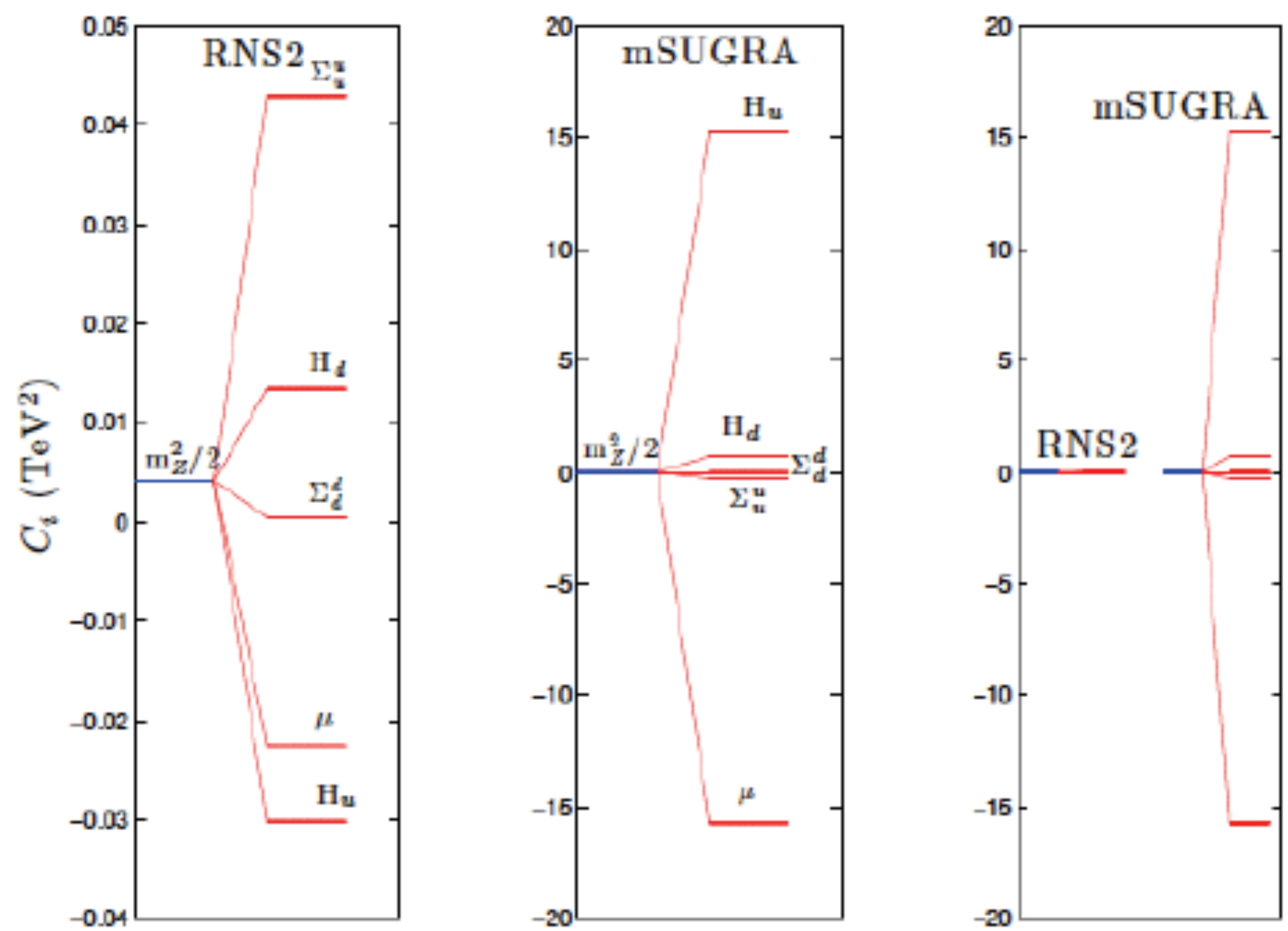
$m_0 = 7025$ GeV, $m_{1/2} = 568.3$ GeV. $A_0 = -11426.6$ GeV, $\tan\beta = 8.55$ with $\mu = 150$ GeV and $m_A = 1000$ GeV

RNS

- $C_{\Sigma_u^u} \sim (205\ \mathrm{GeV})^2$
- $C_{H_d} \sim (114\ \mathrm{GeV})^2$
- $C_{\Sigma_d^d} \sim (22\ \mathrm{GeV})^2$
- $C_\mu \sim -(148\ \mathrm{GeV})^2$
- $C_{H_u} \sim -(173\ \mathrm{GeV})^2$
- $m_Z^2/2 \simeq (65\ \mathrm{GeV})^2$

mSUGRA

- $C_{H_u} \simeq (3.87\ \mathrm{TeV})^2$
- $C_\mu \simeq -(3.93\ \mathrm{TeV})^2$



large cancellations

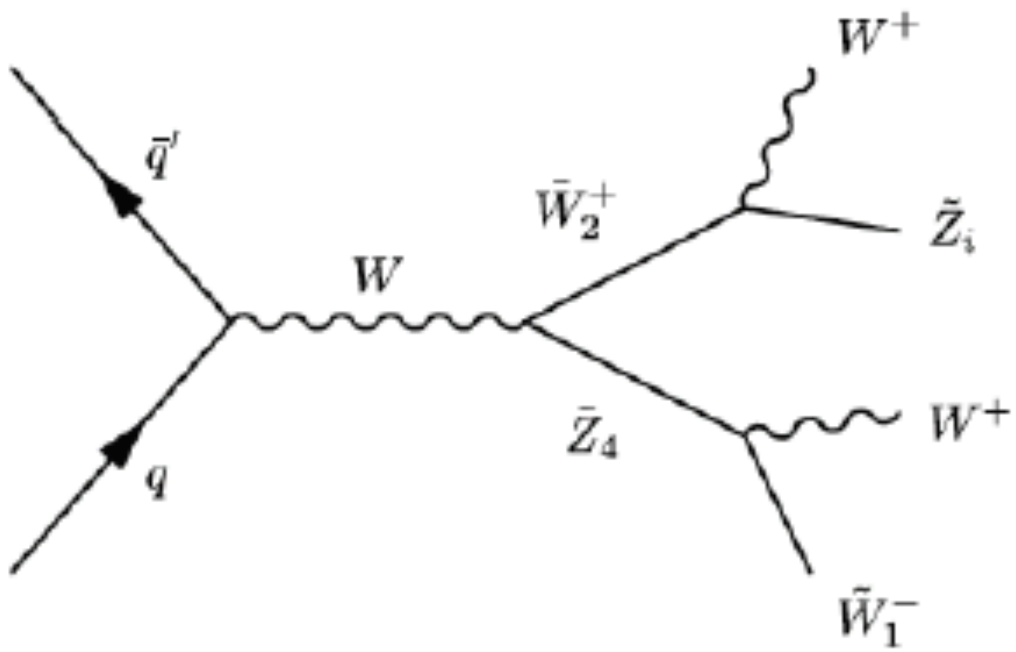
SUSY spectra from radiatively-driven natural SUSY (RNS)

scan NUHM2 space:

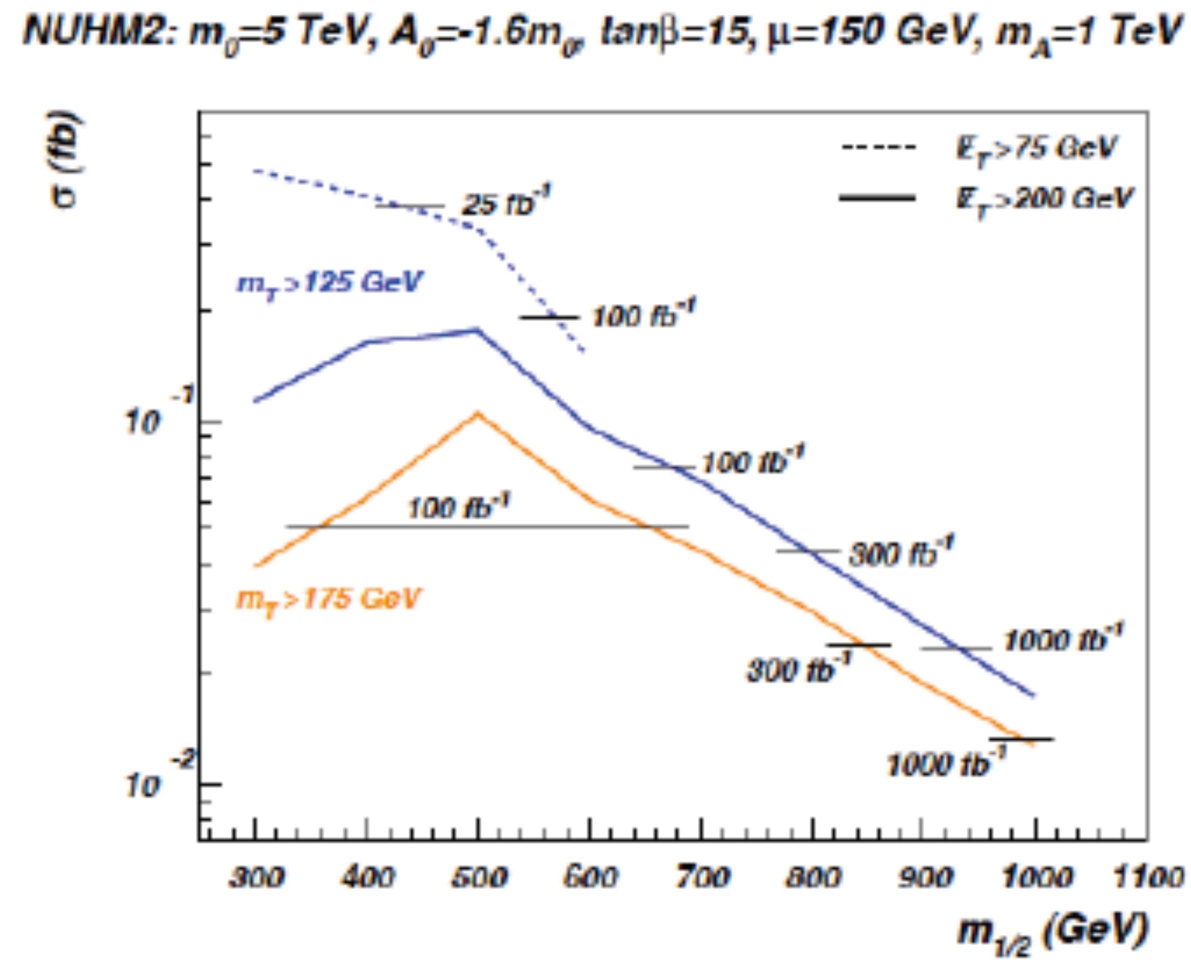
- light higgsino-like $\widetilde{W}_1$ and $\widetilde{Z}_{1,2}$ with mass $\sim 100-300$ GeV,
- gluinos with mass $m_{\tilde{g}} \sim 1-4$ TeV,
- heavier top squarks than generic NS models: $m_{\tilde{t}_1} \sim 1-2$ TeV and $m_{\tilde{t}_2} \sim 2-5$ TeV,
- first/second generation squarks and sleptons with mass $m_{\tilde{q},\tilde{\ell}} \sim 1-8$ TeV. The $m_{\tilde{f}}$ range can be pushed up to 20-30 TeV if non-universality of generations with $m_0(1,2) > m_0(3)$ is allowed.

parameter	RNS1	RNS2	NS2
$m_0(1,2)$	10000	7025.0	19542.2
$m_0(3)$	5000	7025.0	2430.6
$m_{1/2}$	700	568.3	1549.3
A_0	-7300	-11426.6	873.2
$\tan\beta$	10	8.55	22.1
μ	150	150	150
m_A	1000	1000	1652.7
$m_{\tilde{g}}$	1859.0	1562.8	3696.8
$m_{\tilde{u}_L}$	10050.9	7020.9	19736.2
$m_{\tilde{u}_R}$	10141.6	7256.2	19762.6
$m_{\tilde{e}_R}$	9909.9	6755.4	19537.2
$m_{\tilde{t}_1}$	1415.9	1843.4	572.0
$m_{\tilde{t}_2}$	3424.8	4921.4	715.4
$m_{\tilde{b}_1}$	3450.1	4962.6	497.3
$m_{\tilde{b}_2}$	4823.6	6914.9	1723.8
$m_{\tilde{\tau}_1}$	4737.5	6679.4	2084.7
$m_{\tilde{\tau}_2}$	5020.7	7116.9	2189.1
$m_{\tilde{\nu}_\tau}$	5000.1	7128.3	2061.8
$m_{\widetilde{W}_2}$	621.3	513.9	1341.2
$m_{\widetilde{W}_1}$	154.2	152.7	156.1
$m_{\widetilde{Z}_4}$	631.2	525.2	1340.4
$m_{\widetilde{Z}_3}$	323.3	268.8	698.8
$m_{\widetilde{Z}_2}$	158.5	159.2	156.2
$m_{\widetilde{Z}_1}$	140.0	135.4	149.2
m_h	123.7	125.0	121.1
$\Omega^{std}_{\widetilde{Z}_1} h^2$	0.009	0.01	0.006
$BF(b \to s\gamma) \times 10^4$	3.3	3.3	3.6
$BF(B_s \to \mu^+\mu^-) \times 10^9$	3.8	3.8	4.0
$\sigma^{SI}(\widetilde{Z}_1 p)$ (pb)	1.1×10^{-8}	1.7×10^{-8}	1.8×10^{-9}
Δ	9.7	11.5	23.7

Distinctive new signature for LHC: same-sign dibosons from models with light higgsinos



HB, Barger, Huang, Mickelson, Mustafayev, Sreethawong, Tata, arXiv:1302.5816, (PRL in press)



- *exactly* 2 isolated same-sign leptons with $p_T(\ell_1) > 20$ GeV and $p_T(\ell_2) > 10$ GeV,
- $n(b-jets) = 0$ (to aid in vetoing $t\bar{t}$ background).
- $m_T^{\rm min} \equiv \min\left[m_T(\ell_1,\not{E}_T), m_T(\ell_2,\not{E}_T)\right] > 125$ GeV

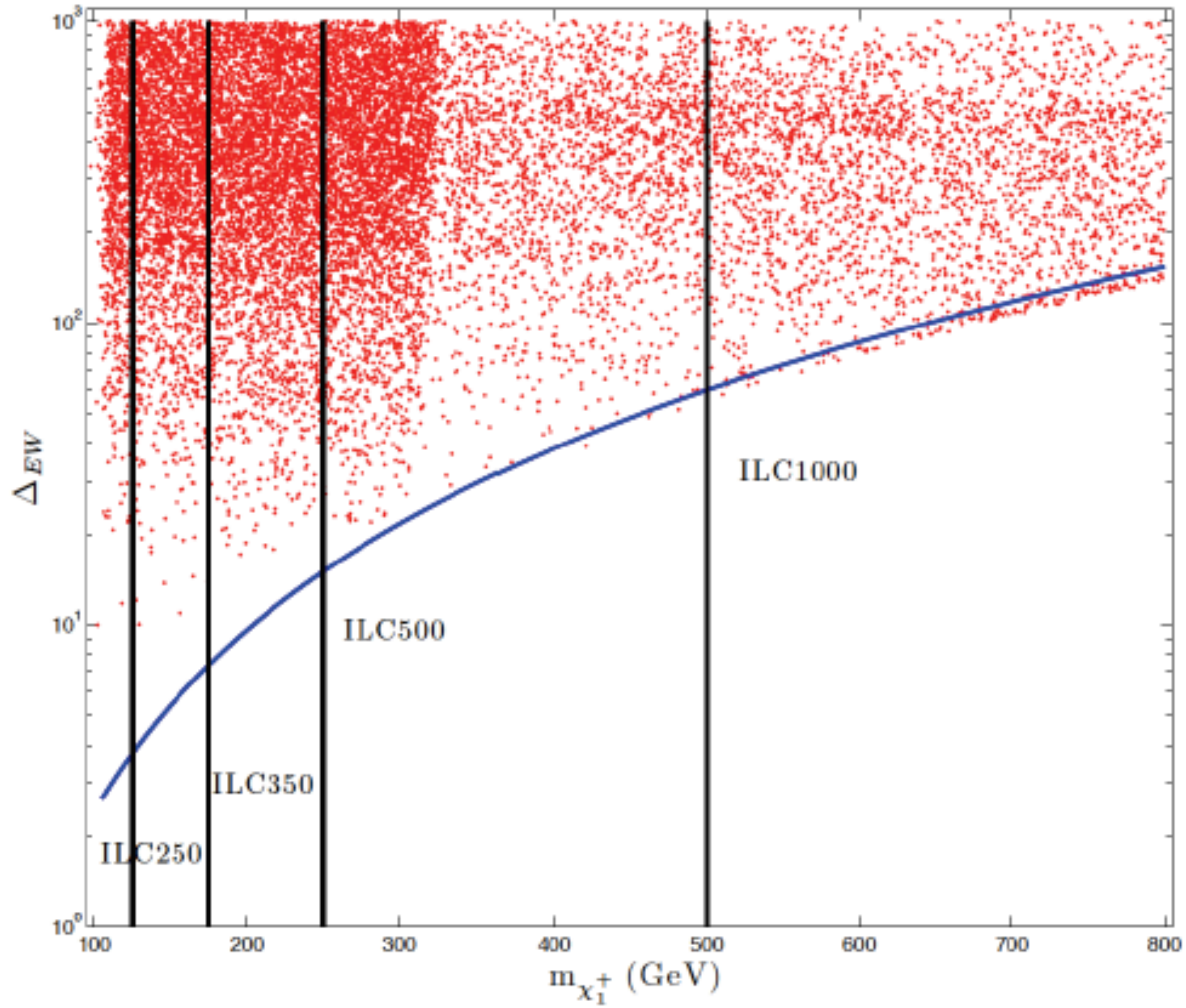
$\not{E}_T' > 200$ GeV

Int. lum. (fb^{-1})	$m_{1/2}$ (GeV)	$m_{\tilde{g}}$ (TeV)	$m_{\tilde{g}}$ (TeV) [$\tilde{g}\tilde{g}$]
10	400	0.96	1.4
100	840	2.0	1.6
300	920	2.2	1.8
1000	1000	2.4	2.0

Reach at LHC14 exceeds usual gluino pair search!

Smoking gun signature: 4 light higgsinos at ILC!

$$e^+e^- \to \tilde{W}_1^+\tilde{W}_1^-,\ \tilde{Z}_1\tilde{Z}_2$$



$$m_{\tilde{W}_1^\pm},\ m_{\tilde{Z}_{1,2}}$$

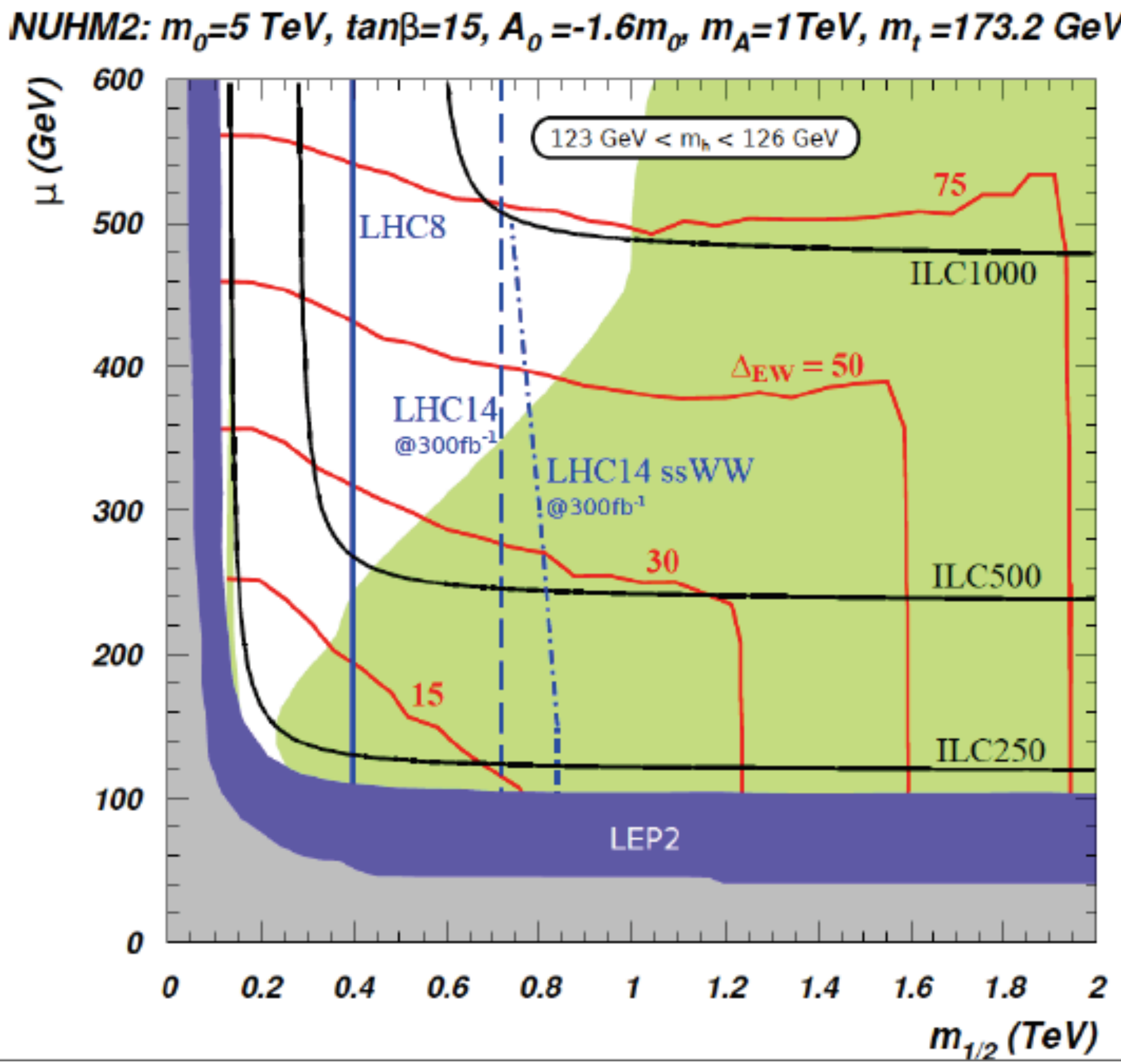
$$\sqrt{s} \sim \sqrt{2\Delta_{EW}}m_Z$$

ILC/CLIC have capability to measure SUSY parameters and actually reconstruct

$$\Delta_{EW}$$

measure and check if nature is EWFT'd?

LHC/ILC complementarity



While LHC has some capacity, it will require ILC to draw the story of SUSY electroweak naturalness to a conclusion!

A. Mustafayev plot

Post LHC8 SUSY benchmarks for ILC physics

HB and Jenny List

arXiv:1205.6929

website:

http://www-flc.desy.de/ldcoptimization/physics.php

LHA files available

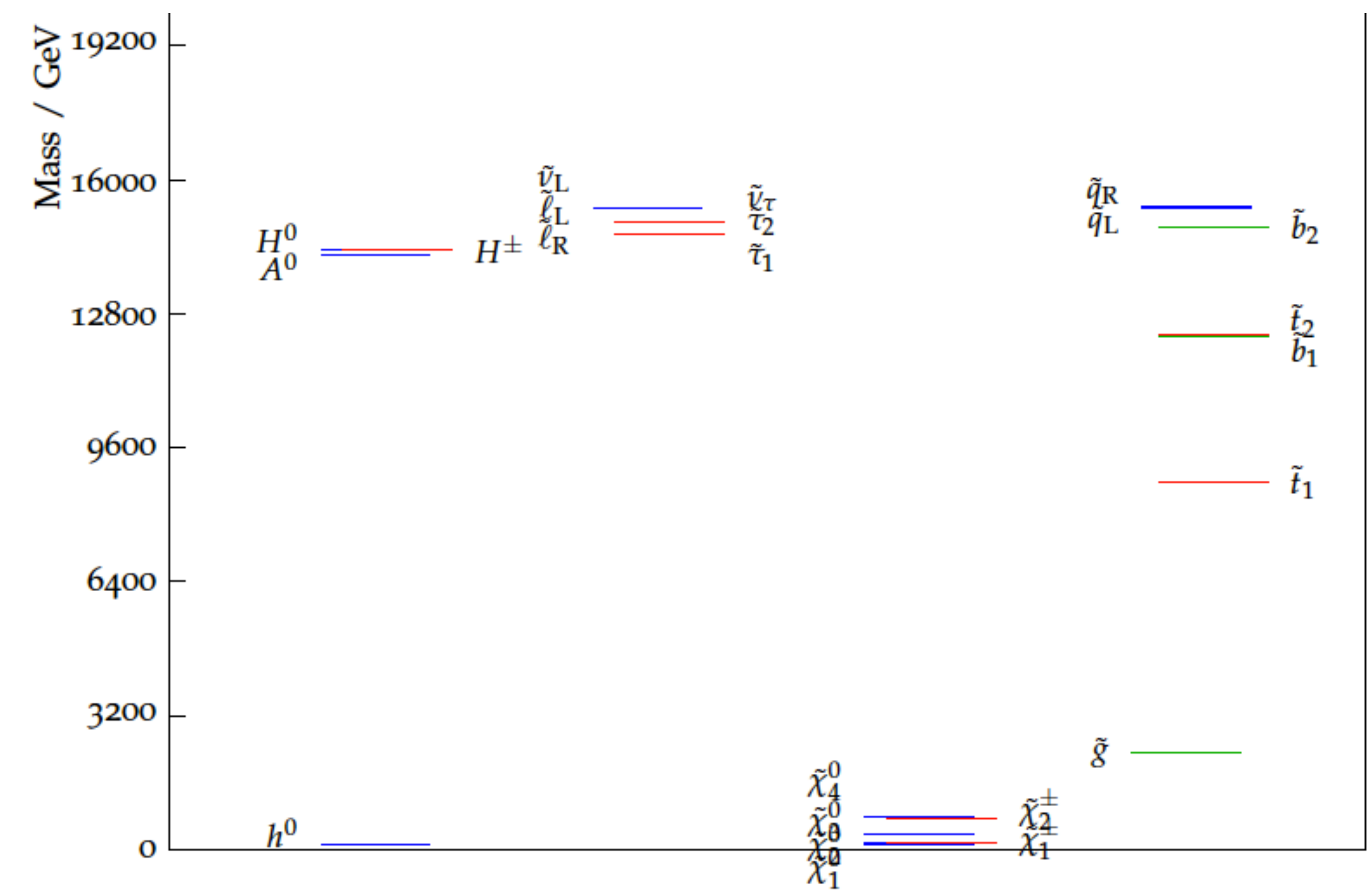
mSUGRA/CMSSM: HB/FP region

Due to m(h)=125 GeV need for A0.ne.0,
HB/FP region moves much further out in m0

In spite of low mu, heavy stops lead to
large EW finetuning

At LHC: gluino pair production:
reach to m(gl)~1.8 TeV for 300 fb-1

At ILC, various mixed
higgsino-gaugino pairs
accessible

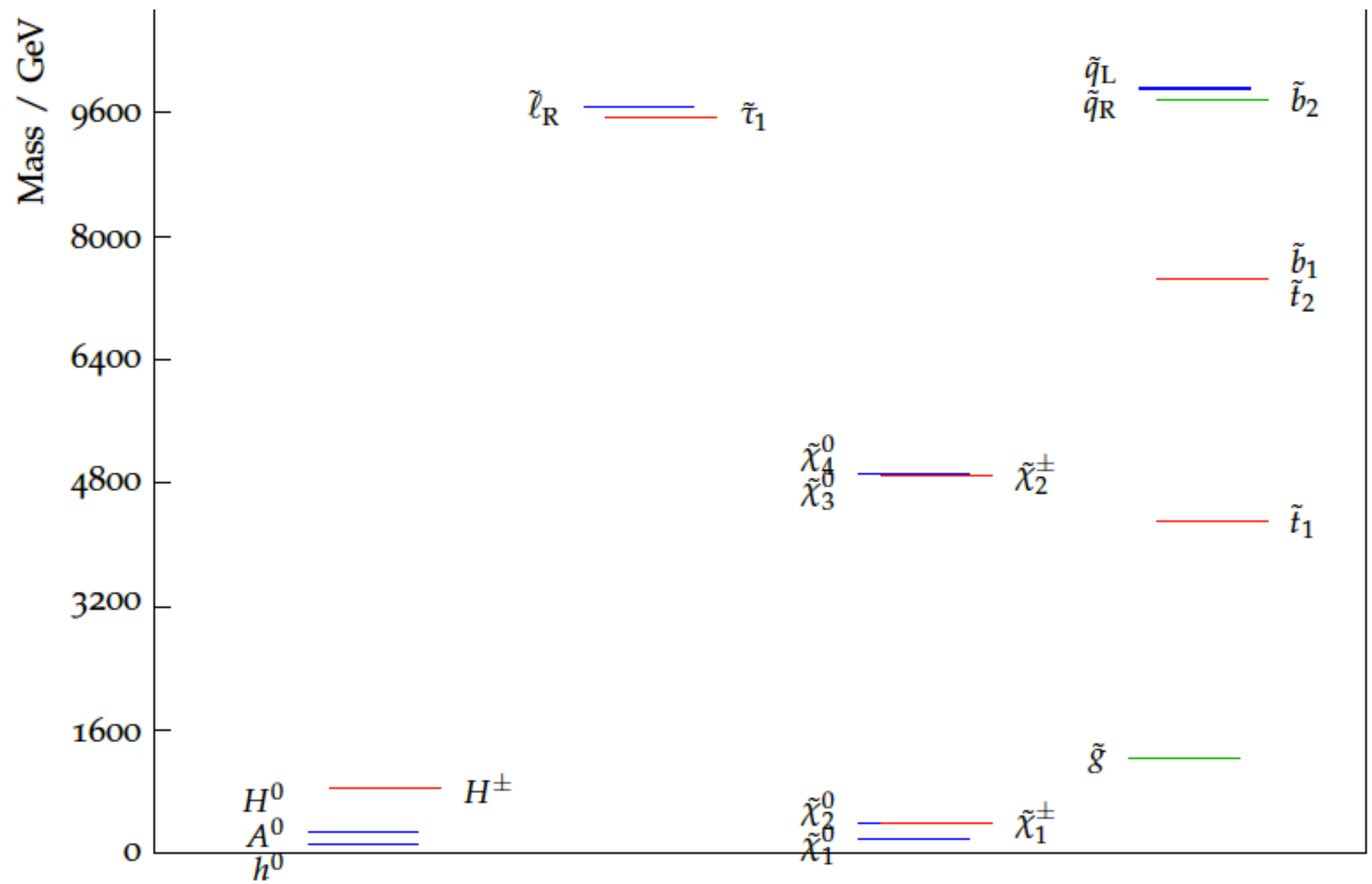


NUHM2 model:
in SU(5) & SO(10), Higgs and matter live in different representations: non-universality expected

$$m_{H_u} \neq m_{H_d} \neq m_0$$

LHC:
gluino pairs;
inos-> trileptons;
A,H direct production

ILC:
Zh, Ah, ZH production;
low lying EW-ino pairs



Non-universal gaugino masses:
Gauginos get mass differently in SUGRA:

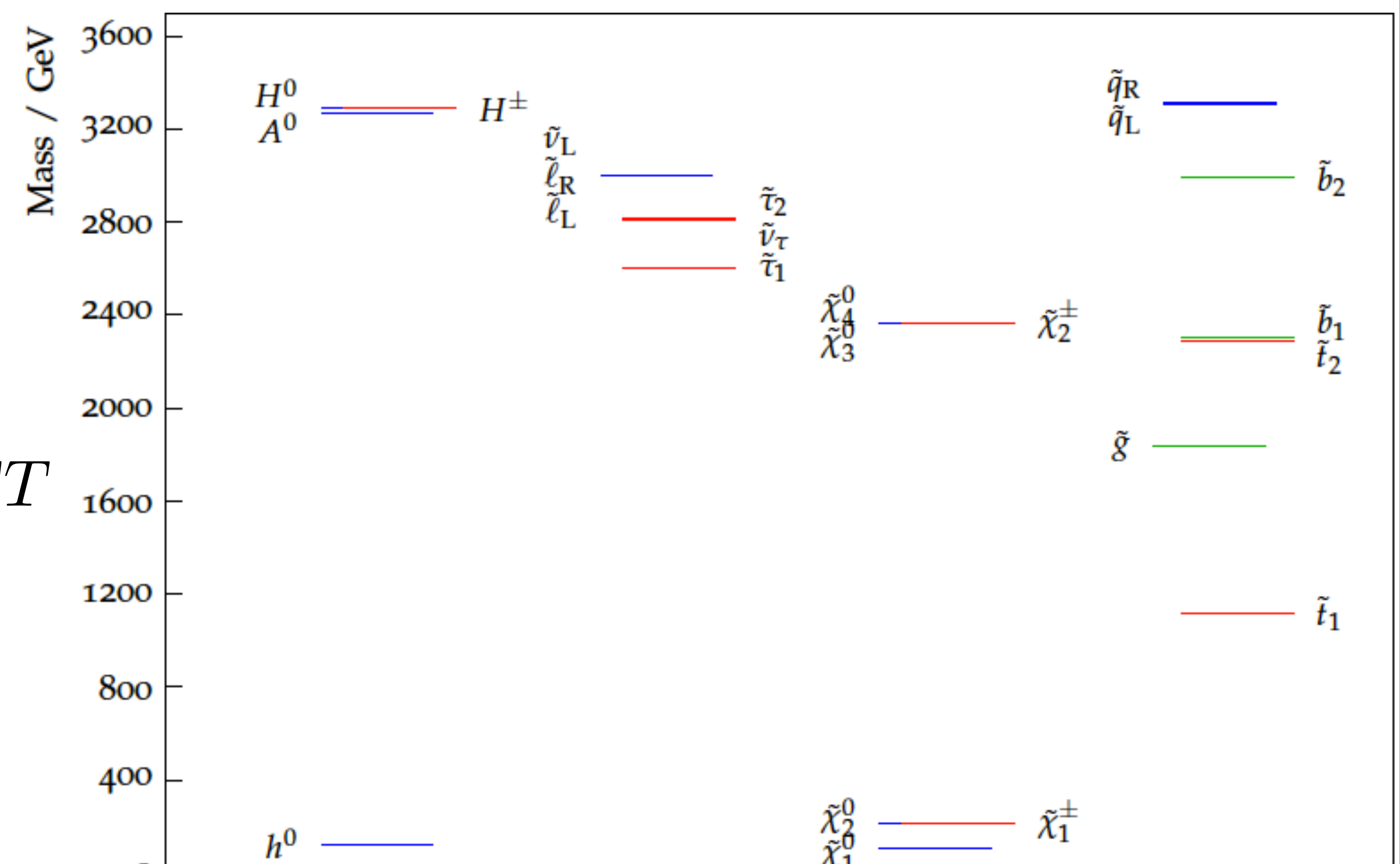
$$\mathcal{L}_F^G = -\frac{1}{4} e^{G/2} \frac{\partial f^*_{AB}}{\partial \hat{h}^{*j}} \big|_{\hat{h}\to h} \left(G^{-1}\right)^j_k G^k \bar{\lambda}_A \lambda_B$$

LHC:
clean trileptons :

$$pp \to \tilde{\chi}_1^{\pm} \tilde{\chi}_2^0 \to WZ + MET \to 3\ell + MET$$

ILC:

$$e^+e^- \to \tilde{\chi}^{\pm}\tilde{\chi}^{\mp} \to W^+W^- + MET$$



Kallosh-Linde-Olive; Kane et al. G2MSSM string-inspired with moduli stabilization

$$m_{3/2},\ m_{\tilde{q},\tilde{\ell}} \sim 25 - 100\ TeV$$

$$gauginos:\ AMSB\ form\ with\ wino = LSP$$

LHC:

gluino pairs with

$$\tilde{g} \to tb\tilde{\chi}_1^{\pm}$$

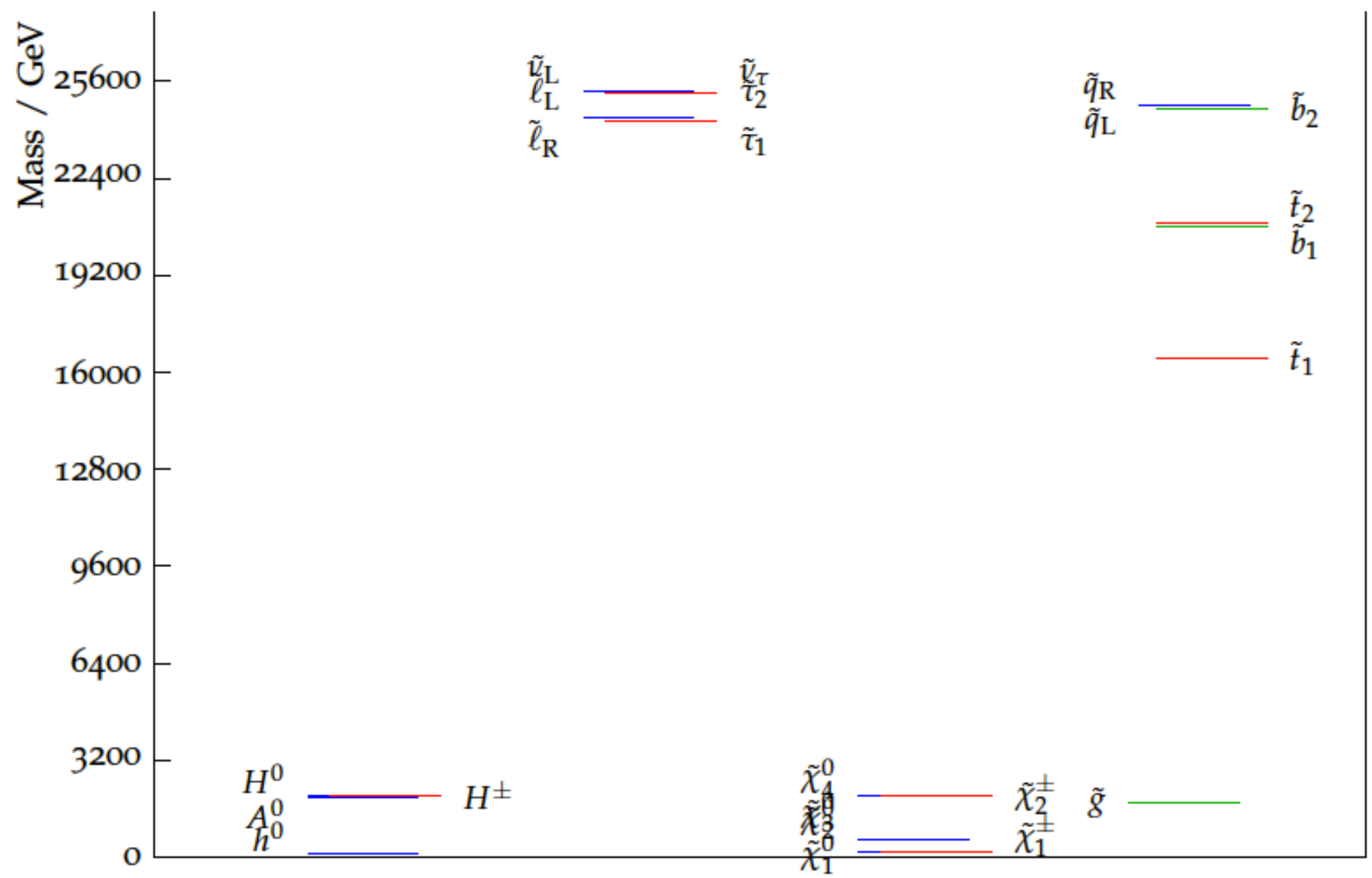
displaced vertices?

ILC:

$$e^+e^- \to \tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}\gamma$$

small mass gap~200 MeV

$$\tilde{\chi}^{\pm} \to \tilde{\chi}_1^0\pi^{\pm}$$



Normal scalar mass hierarchy (NMH): reconciles

$$(g-2)_\mu \ with \ BF(b \to s\gamma)$$

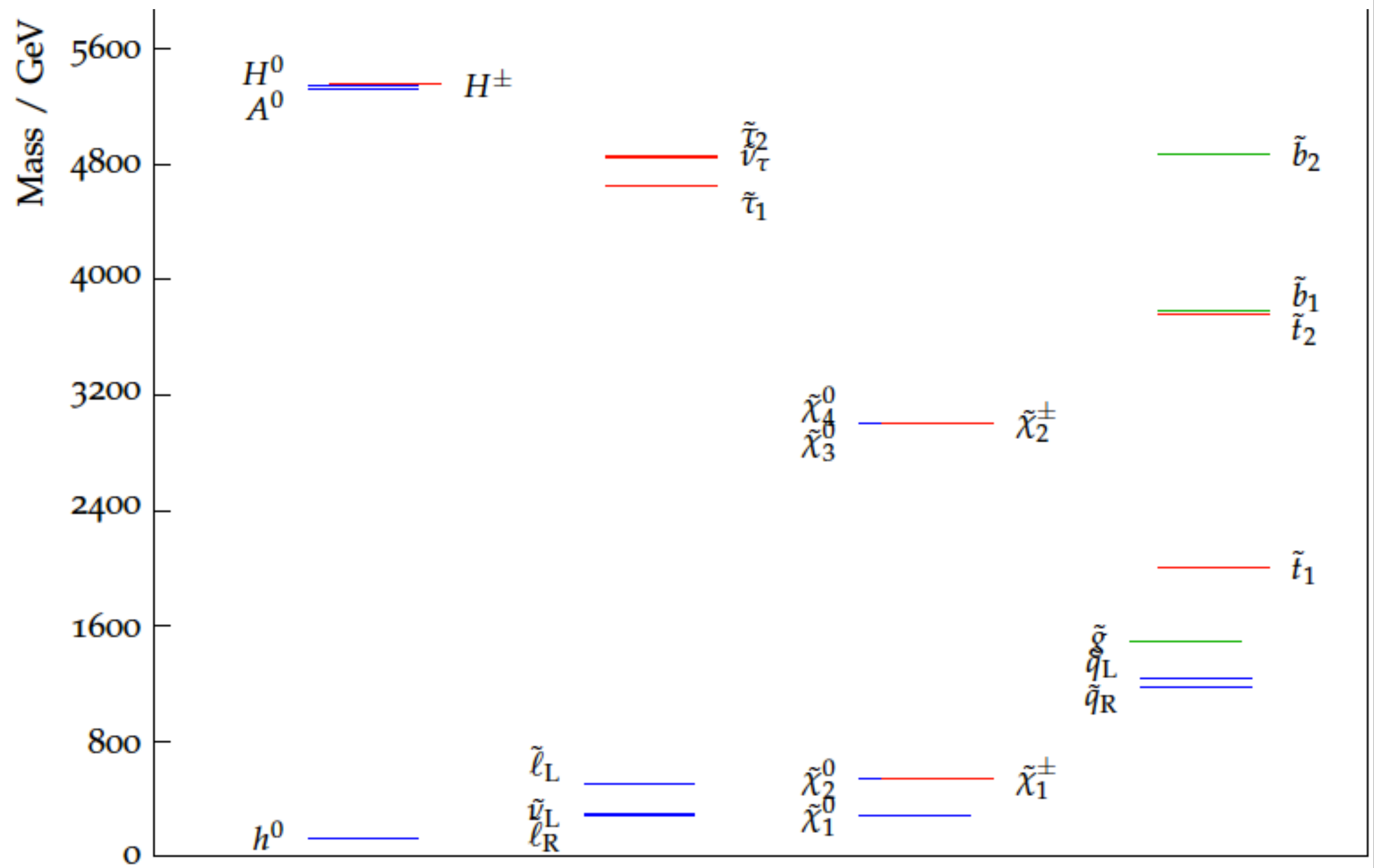
split generation with $m_0(1,2) \ll m_0(3)$

LHC:

$$pp \to \tilde{q}\tilde{q}, \ \tilde{q}\tilde{g}, \ \tilde{g}\tilde{g} \quad ?$$

ILC:

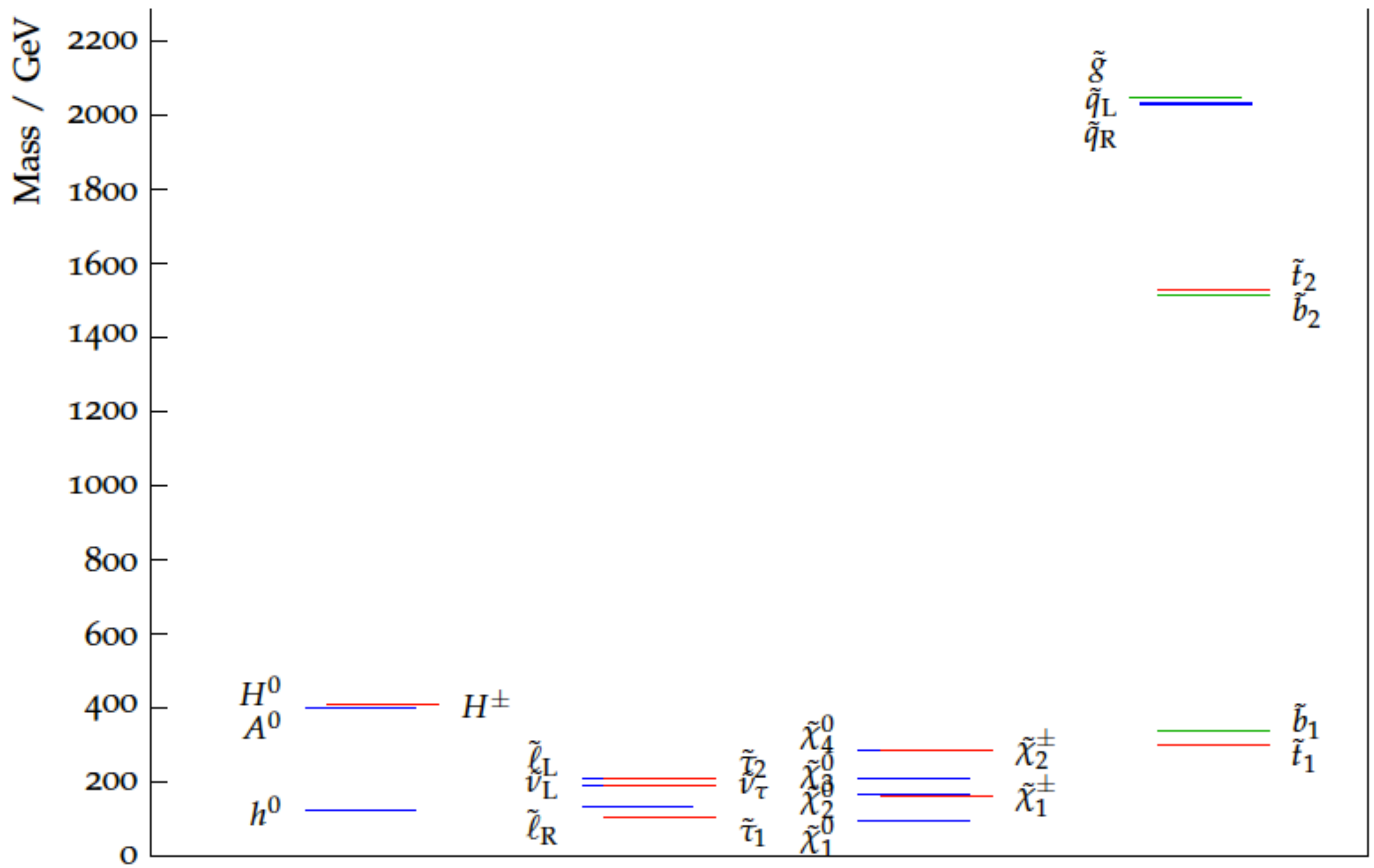
$$e^+e^- \to \tilde{e}_R \bar{\tilde{e}}_R \to e^+e^- + ME$$



A pMSSM model looks like SPS1a' but now LHC-compatible:

LHC:
light stop, sbottom;
sleptons;
EWinos;
m(gluino) raised up
compared with SPS1a'

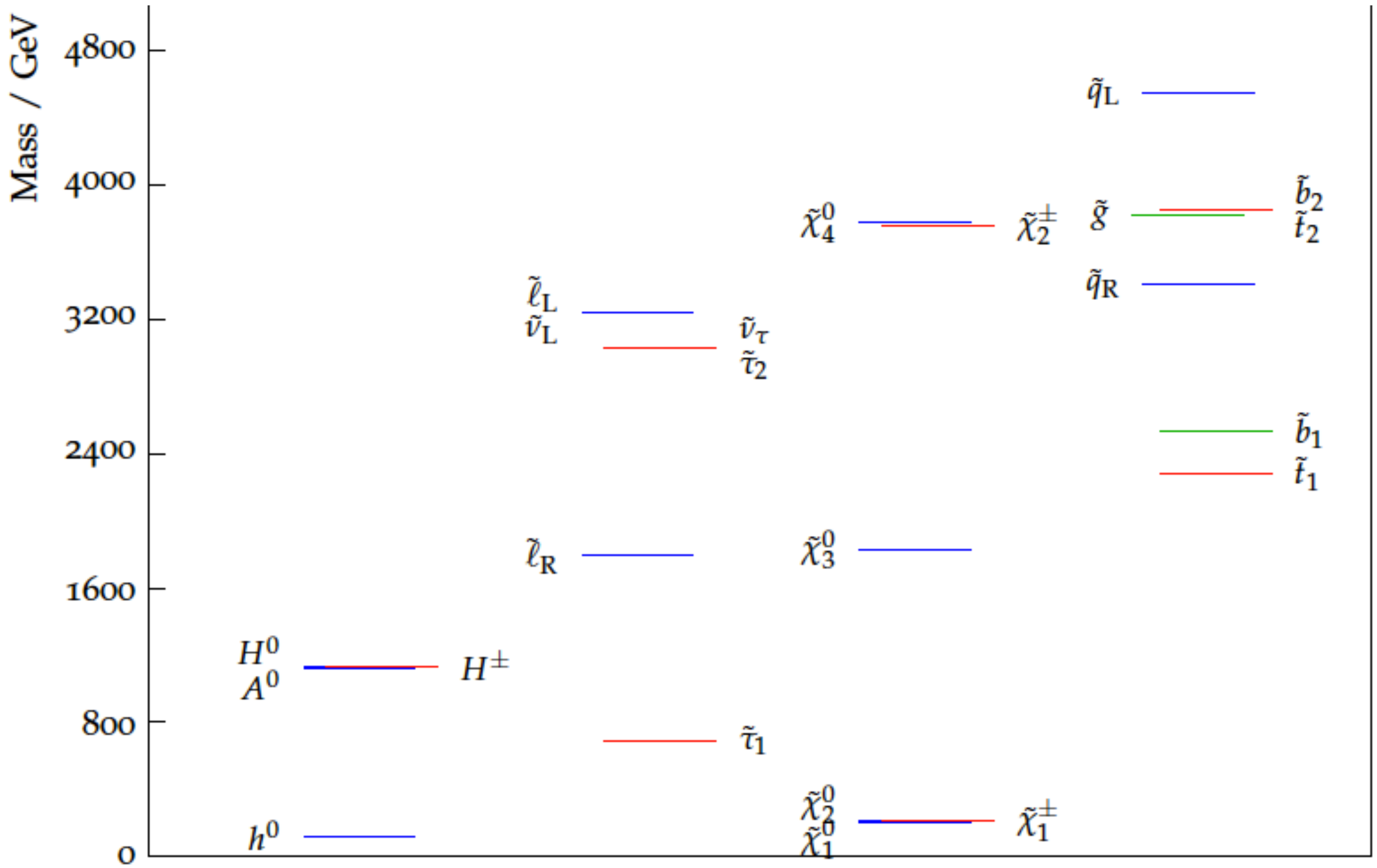
ILC:
sleptons,
EWinos all accessible!
previous SPS1a' studies applicable
m(h)~125 GeV



Brummer-Buchmueller: string-inspired mixed gauge-gravity mediation

LHC:
very hard to see

ILC:
higgsino pair production with 1-3 GeV mass gap



Conclusions:

- Radiative natural SUSY:
  reconciles m(h)~125 GeV with EW finetuning
- light higgsinos: m(higgsino)~m(higgs)
  new signatures for LHC: SS-dibosons;
- can elude LHC searches without compromising naturalness
- smoking gun signature: higgsino pairs at ILC: must see!
- variety of theory-motivated benchmarks with
  m(h)~125 GeV beyond LHC8 reach
  but discoverable at ILC

LHC may get lucky, but ILC is required to completely probe weak scale SUSY